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MATERIAL DATABASE FOR ADDITIVE MANUFACTURING TECHNIQUES

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13. ABSTRACT ***(Maximum 200 Words)***

This report details material testing and results for a set of materials used in additive manufacturing for the Printable Materials With Embedded Electronics (PRIME2) Science and Technology (S&T) program. These material results are presented for specific printers and print directions.

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EXECUTIVE SUMMARY

This report details several materials used in additive manufacturing and the United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) manufacturing capability associated with the PRIntable Materials With Embedded Electronics (PRIME2) Science and Technology (S&T) program. A full materials database is included.

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I. INTRODUCTION

The United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Weapons Development and Integration (WDI) Directorate has a Fiscal Year (FY) 2016 Science and Technology (S&T) program known as PRIntable Materials With Embedded Electronics (PRIME2). PRIME2 will integrate Radio Frequency (RF) and electronics into additive manufacturing processes to reduce size, weight, and overall cost of these components and subsystems. This program will advance the state of the art in printable electronics and deliver a materials database, process development, modeling, and simulation of Three-Dimensional (3-D) printed objects with embedded conductive elements, passive prototypes, and RF prototypes. PRIME2 will create a new fabrication capability (applied to electronics and RF technology areas), weight reduction, higher reliability, and on-demand (local and immediate) spare components in the field.

II. BACKGROUND

Additive manufacturing is a rapidly maturing process by which digital 3-D design data are used to build up components in layers by depositing materials or through the melting and sintering of (powdered) materials to create solid structures. These materials can be conductive (metal) or nonconductive (polymer) and have complex material properties that are dependent on print parameters.

In the past 5 years, additive manufacturing has quickly gained adoption and acceptance as a valuable manufacturing technology. There are many different types of printers, including Fused Filament Deposition (FFD), Stereolithography (SLA), and laser sintering. The National Aeronautics and Space Administration (NASA) has a FFD machine on the International Space Station (ISS). As this is a rapidly maturing technology, the number of printers and the expertise in this field is also rapidly expanding. The 4-year hiring trends in the field of additive manufacturing are shown in Figure 1. The number of patents issued worldwide in the field of additive manufacturing is shown in Figure 2. Note that the hiring trends correspond to the last few years when the number of patents bloomed in this area.

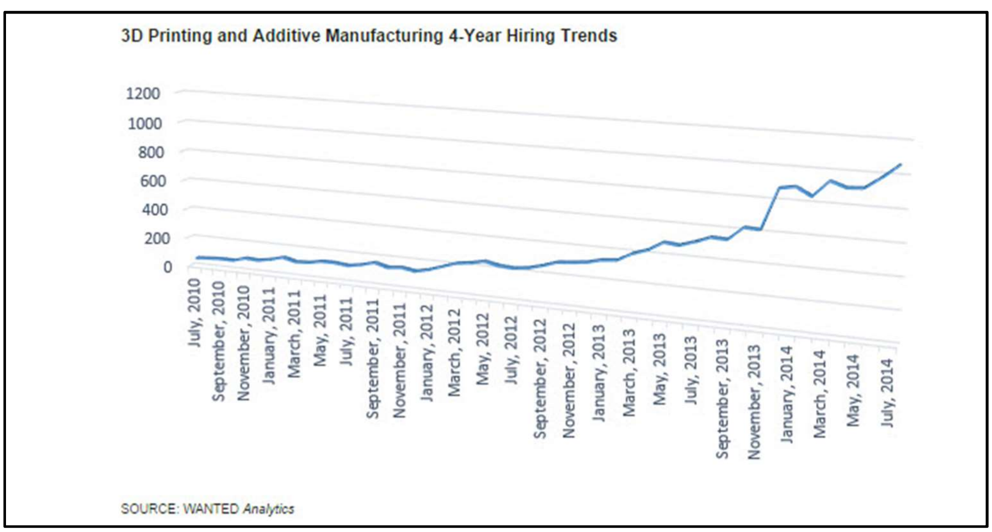

Figure 1. Additive Manufacturing 4-Year Hiring Trends from 2010 to 2014

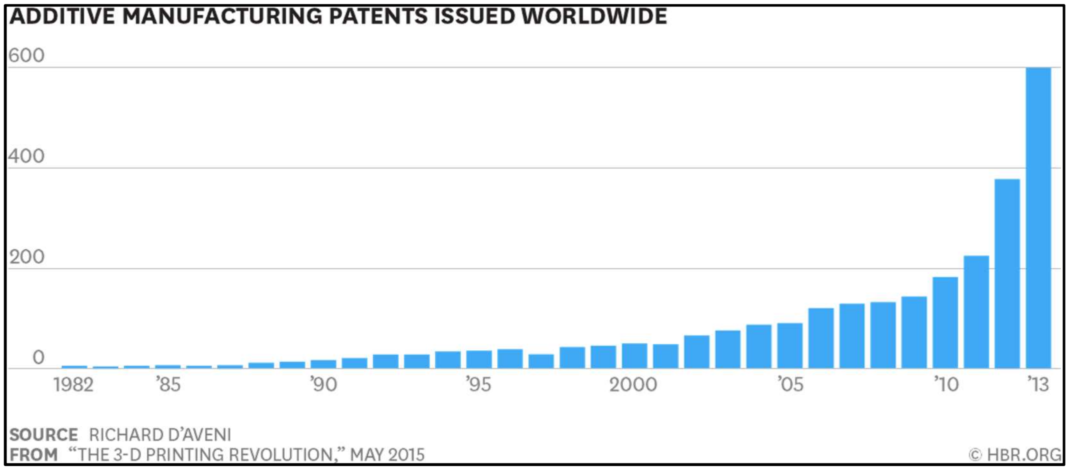

Figure 2. Additive Manufacturing Patents Issued Worldwide from 1982 to 2013

Additive manufacturing brings a new capability that can be explored across all technology areas for benefits and use. The benefits can be many and varied, resulting in components that are not achievable utilizing traditional subtractive machining methods, lower weight components, low cost, local and immediate prototyping, and component creation. One of the most important aspects of the PRIME2 program is the creation of processes to achieve a means by which these modules, components, or subsystems are printed with different conductivities or embedded elements. Throughout process development, PRIME2 will explore the limitations and capabilities of additive manufacturing as it applies to military applications, specifically for the AMRDEC. PRIME2 is developing pervasive technology that is useful across multiple systems in support of the Warfighter.

Traditionally, electronic components and RF components are assembled piecemeal and are not part of the additive manufacturing process. PRIME2 seeks to exploit the opportunity to integrate electronic components during the mechanical additive manufacturing process. PRIME2 is developing enabling technologies to print an entire printed wiring board with embedded passive components and integrated RF structures in one step. PRIME2 is working to achieve this and document the processes that makes it possible. Connectors could be printed to achieve commercially available connectivity in a design specific to the available working space.

PRIME2 has documented several material properties for components created using the additive manufacturing method. In addition, other prototype structures have been manufactured and evaluated. This report is found in Reference 1.

III. ADDITIVE MANUFACTURING

Additive manufacturing, known as 3-D printing, is rapidly developing to meet the needs of a wide range of commercial and military applications. 3-D printing is typically used in prototype development to reduce costs and development time compared to traditional manufacturing. For example, 3-D printing enables concept to prototype in less than a day at $5 to 8 per cubic inch of material [2], and it has been used to fabricate prototypes, tooling, fixtures, and forms to test design fit [2]. 3-D printing allows free complexity and integration of parts that are too costly or even impossible for traditional manufacturing [3]. In some cases, printing requires no tool

adjustments to fabricate hollow and buried structures; therefore, interconnects and connectors are simply printed where they are needed within the volume. This design freedom is particularly relevant to RF antennas where directivity and efficiency are currently limited by manufacturing constraints and losses in conductive feeds [4-6].

With respect to enhancing a supply chain, 3-D printing competes with traditional machining on cost and quality for low- to mid-grade production runs by eliminating upfront setup and tooling [7]. 3-D printing reduces assembly costs by eliminating interconnects and fasteners and improves readiness by offering on-demand low-rate production [8, 9]. 3-D printing also enables rapid design iterations and complexity, which improve modernization through customization, increased functionality, and customer responsiveness. 3-D printing mitigates many supply challenges by enabling immediate customizable production with a turn time on the order of days rather than weeks.

Material performance and control with 3-D printing are challenging due to effects of infill, print orientation, and surface roughness on performance. Porous infills are used in 3-D printing to decrease print time, but adding voids to the material affects the final properties. Typically, these issues are addressed through characterization of the printed material.

IV. MATERIALS AND PROCESSES

As additive manufacturing becomes a household term, printing techniques, such as FFD, SLA, Ink Dispensing, and Microjetting, are enabling diverse and distinct functions and applications.

A variety of materials are available for additive manufacturing. These include both conductors and dielectrics. However, many of these materials compromise mechanical or electrical performance to enable ease of manufacture. In addition, many of these materials often require incompatible post-processing, such as thermal cures that can disrupt underlying structural elements. The characterizations of FFD (also known as Fused Deposition Modeling (FDM)), SLA, inkjet deposition, and microdispensable dielectric materials are presented herein, along with the characterizations of FDM, inkjet deposition and microdispensable conductive materials.

Over 35 dielectric materials suitable for FDM, SLA, and inkjet were evaluated in an effort to demonstrate a material set that had sufficient process compatibility to be co-fabricated that yielded electronic structures embedded within structural elements, yet also possessed sufficient performance to enable high-frequency RF use. A select set of dielectrics is shown in Table 1. For dielectrics, relative permittivity and loss tangent are critical for implementing RF systems. In general, most additively manufacturable materials are polymeric, with a dielectric constant that falls within the range of 2 to 6. However, some unique materials are available. In particular, composite materials incorporating metals and ceramics provide enhanced dielectric constants that may be useful in RF design. Some polymer matrix composites can yield low levels of conductivity. These levels are not sufficient for quality RF components but could be useful for Direct Current (DC) signals. Based on these results, dielectrics, such as High Impact Polystyrene (HIPS), polyethylene, and polyetherimide (PEI), are of interest for further development.

Table 1. Dielectrics for Additive Manufacturing

Material	Process	Infill (%)	Rel. Permittivity	Loss Tangent (@200MHz)	Solvent	Operating Temp (°C)
PLA	FDM	100	2.72	0.008	Methylene Chloride	65
ABS	FDM	100	3.5	0.005	Acetone	110
Copper PLA Composite	FDM	20	8.42	0.007	Methylene Chloride	65
HIPS	FDM	20	2.58	0.0001	Limonene	100
Nylon	FDM	100	3.01	0.02	Formic Acid	70
PEEK	FDM	100	3.18	0.003	Dimethyl Sulfoxide	200
UV Resin (PMMA)	SLA	100	5.11	0.045	Methylene Chloride	100
Ceramic UV Resin	SLA	100	5.28	0.014	Methylene Chloride	100
Polyethylene	FDM	100	2.26	0.0002	Xylene	80
Polycarbonate	FDM	100	3.64	0.004	Acetone	140
Polyetherimide (Ultem)	FDM	100	3.15	0.0013	Trichloroethylene	210
SU-8	Inkjet	100	3.24	0.015	Cyclopentanone	200

Also included in the table are material characteristics that are beneficial for co-fabrication of these materials with other materials and using other processes. The existence of a suitable solvent for the dielectric material can be helpful in preparing printed substrate surfaces for further additive manufacturing steps. In addition, the melt temperature of the material is important for post-processing steps that may be required when depositing certain conductive materials.

The effects of infill on a dielectric substrate are substantial. For example, using a simple Polylactic Acid (PLA) based 2 millimeters (mm) thick puck for evaluation printed with 100 percent (%) infill, the permittivity measured 3.41. When printed with 20% infill using a nominal slicing profile (three solid shell layers on top and three solid shell layers on bottom), the permittivity measured 2.48. With the same 20% infill and only one solid shell layer on top and bottom, permittivity measured 1.82. This is due to the increase in air content within the structure. The resulting structure is less solid which results in a structure that is less rigid. These design opportunities are abundant in additive manufacturing, allowing design freedom that is only limited by the material strength requirements.

A set of eight conductive materials was also evaluated, as shown in Table 2. The selected materials focused on inkjet and microdispense technologies. These materials demonstrated a wide range of conductivities. Organic conductors were at the low end of the range and were not suitable for RF applications. Conductive epoxies, such as Epoxies Etc. 40-3920, have desirable features of room temperature curing. This makes them more readily compatible with other additive manufactured substrates. However, their conductivities were an order of magnitude below the nanoparticle inks that are used in aerosol and inkjet techniques. The nanoparticle inks, however, exhibit no better than 50% of the conductivity of solid metal conductors, such as electroplated copper. In addition, they require elevated temperatures to sinter the nanoparticles into a conductive sheet. These elevated temperatures can cause incompatibility with certain additively manufactured dielectric materials.

Table 2. Conductors for Additive Manufacturing

Material	Process	Cure Process	Conductivity (S/m)
Silver-NanoParticle	Inkjet, Aerosol	150°C, Photonic	$4x10^7$
Copper-NanoParticle	Inkjet, Aerosol	Photonic	$3x10^7$
Epoxies, Etc. 40-3920	Microdispense	Room Temp Air	$5x10^5$
DuPont CB028	Microdispense	160°C	$4x10^6$
Voxel8 Silver Ink	Microdispense	Room Temp Air	$2x10^6$
Plexcore Organic	Inkjet, Aerosol	Room Temp Air	100
Graphene	Inkjet, Aerosol	110°C	$4.5x10^4$
Solid Copper	Electroplate	None	$6x10^7$

A full spreadsheet of materials and material properties is included in the appendix.

Based on the collected data, a subset of materials was further investigated for co-fabrication and realization of RF structures. Considerations during the down selection process included material performance, material compatibility, availability and capability of additive manufacturing tools, and the desired RF component and designs. In particular, standard PLA, standard acrylonitrile butadiene styrene (ABS), polyether ether ketone (PEEK), HIPS, and ULTEM were selected for further dielectric investigation. Silver nanoparticle inkjet material and room temperature cured silver paste from Voxel8 were selected for further conductor investigation. The additive processes and their respective materials are discussed in Sections IV.A through C.

A. Fused Filament Deposition

FFD uses a continuous filament of a thermoplastic material fed from a spool through a moving, heated printer extruder head. Molten material is forced out of the printhead's nozzle and is deposited on the growing work piece to form a 3-D object.

1. PLA

PLA is a biodegradable thermoplastic polyester. It is a commonly manufactured from renewable resources such as cornstarch, tapioca roots, and sugarcane. PLA is harder that ABS plastic, has a lower melting temperature (180-220 °C), and a glass transition temperature between 60 and 65 °C. It is dimensionally stable and can be printed with or without a heated build plate. It adheres easily to borosilicate glass, Lexan and polycarbonate sheets, blue painters tape, polyimide (Kapton) tape, and so forth. PLA is often used in model making applications and may be treated with a wide range of post-processing techniques, as shown in Figure 3. PLA prints may have slight dimensional variations compared to other materials. Color and brand have some small effects on printing.

Figure 3. Structures Printed Using PLA

2. ABS

ABS is a common thermoplastic. It is less brittle (tougher) than PLA. With a glass transition temperature approximately 105 °C, it requires a higher extruder temperature than PLA, 230 °C ±15 degrees (°). ABS creates mild fumes when being extruded, and printers should be operated in a well-ventilated area. ABS requires a heated build plate that is heated to approximately 110 °C due to its tendency to warp when printing larger prints. It adheres easily to borosilicate glass, Lexan and polycarbonate sheets blue painters tape, Polyimide (Kapton) tape, and so forth. Figure 4 shows examples polymer filaments.

Figure 4. ABS Polymer Filaments

3. TPE

The flexibility of the Thermoplastic Elastomer (TPE) filament makes it quite resilient and sturdy for producing objects with a Shore A hardness of approximately 75-85A. This filament is easily printed in most printers capable of printing PLA or ABS plastics, although it has a slightly higher melting temperature (240 °C) and is ideal for multi-material applications requiring portions of the design to flex, such as shock absorption devices and hinges. Printing TPE benefits from a build plate that is heated to approximately 60 °C and direct drive extruders. Figure 4 is an example of a TPE material print.

Figure 5. TPE Material Print

4. Nylon

Stronger than PLA and more durable than ABS, nylon offers the benefit of a material robust enough for functional parts. Nylon's high melting temperature and low friction coefficient present a versatile printing option that allows flexibility. Figure 6 shows an example of a nylon filament.

Figure 6. Nylon Filament

5. ULTEM

ULTEM offers high thermal resistance, high strength and stiffness, and broad chemical resistance. ULTEM is available in transparent and opaque custom colors as well as glass filled grades. Plus, ULTEM copolymers are available for even higher heat, chemical, and elasticity needs. ULTEM 1000 (standard, unfilled PEI) has a high dielectric strength, inherent flame resistance, and extremely low smoke generation. These high mechanical properties perform in continuous use to 340 °F (170 °C), which makes it desirable for many engineering applications. Figure 7 shows examples of ULTEM prints.

Figure 7. ULTEM Prints

6. PEEK

With its unique mechanical, chemical, and thermal properties, PEEK has many advantages over other polymers and is able to replace industrial materials such as aluminum and steel. It allows its users to reduce total weight, processing cycles, and increase durability. Compared to metals, the PEEK polymer allows a greater freedom of design and improved performance. PEEK is used to fabricate items used in demanding applications, including bearings, piston parts, pumps, High-Performance Liquid Chromatography (HPLC) columns, compressor plate valves, and electrical cable insulation. It is one of the few plastics compatible with ultra-high vacuum applications. Figure 8 shows an example of a PEEK filament.

Figure 8. PEEK Filament

B. Stereolithography

While FFD technology provides a means to rapidly prototype objects, SLA is often better suited for detail and high-speed production. Parts are constructed in a layer-by-layer fashion using photo-polymerization, a process by which Ultraviolet (UV) light causes chains of molecules to link and form polymers that then make up a 3-D solid object. The production of these objects relies on materials that are currently available in many forms, including standard and engineering resins.

1. Standard Resins

The material selection for SLA is more limited than FFD, but general purpose or standard resins have grown to include a variety of colors in varying opacities. Standard resins provide high resolution for applications like visual demonstrations and models.

2. Engineering Resins

Matching the detail provided with standard resins, engineering resins possess additional strength and functionality. The flexible resin variety simulates an 80A durometer rubber, which is often chosen for impact resistance and compression. The tough resin is similar to a finished product formed from ABS plastic. Applications that will undergo high stress and strain are frequently engineered with tough engineering resin, ensuring successful assembly, machining, snap-fits, and living hinge supports. The ceramic resin is UV-curable, with objects often glazed with commercially available coatings after firing. Figure 9 shows examples of flexible, tough, and ceramic engineering resins. Printed items made from this material are safe for food and may be used in the microwave, oven, dishwasher, and freezer.

(a) Flexible *(b) Tough* *(c) Ceramic)*

Figure 9. Engineering Resins

C. Ink Dispensing and Micro-Jetting

EngeniusMicro has developed an in-house own ink microdispensing printhead known as the MicroDispense®, which is available for use under PRIME2. MicroDispense® utilizes positive pressure and a needle valve to accurately dispense incredibly detailed patterns and

circuits on the substrate. The MicroDispense® printhead operates on a 3-axis Computer Numerical Control (CNC) mill, replacing the conventional tool head. It was developed in-house with many of the components, such as valves and nozzles, created and printed using the SLA resin printers. These printers are able to quickly create circuits on par with medium density circuit boards produced through conventional photoresist and etch manufacturing methods.

EngeniusMicro currently utilizes drop-on-demand printing technology through the use of a Fujifilm Dimatix materials printer. Conductive inks are printed on a variety of substrates from as thin as a few microns up to a 25 mm thickness using piezo jets to precisely deposit inks onto the substrate. The print is then submitted to post-processing to sinter the conductive particles in the ink while evaporating away solvents and other volatiles. Using the appropriate ink recipe, this process can produce traces as narrow as 10- and 5-micron (μm) gaps between traces. A number of flexible circuits have been printed in addition to advanced sensors specifically developed to be printed on flexible materials using conductive inks.

1. Continuous Fiber Composites

Continuous fibers composites can be printed simultaneously with polymers to produce stiff and strong composite objects. This enables the ability to embed continuous fibers of carbon fiber, glass fiber, and Kevlar into 3-D printed nylon components.

2. Chopped Carbon Fiber

Chopped carbon fiber composite materials print similarly to the standard printing filaments and do not require special printing equipment. While they do not have the extreme performance characteristics of continuous fiber filaments, they do produce light and strong components.

3. Filled PLA Composites

Filled PLA composite provide the opportunity to print materials with a variety of special characteristics. These composites include iron, stainless steel, bronze, copper, carbon fiber, and wood. These materials allow for a wide variety of properties and finishes.

V. PRINTERS

In-house capabilities include a number of custom-modified 3-D printers as characterized in Section V.A through G. The capabilities, corresponding materials, and applications to the PRIME2 program are presented with a focus on printable electronics and RF structures.

A. Lulzbot Taz Series

Multiple materials can be used on a custom modified Lulzbot Taz Series printer, such as flexible filaments and high-temperature thermoplastics. Differentiators for the Lulzbot Taz series include a unique hexagon all-metal hot end, which enables X and Y. This capability, coupled with the PEI print surface, allows for a variety of materials, as listed in Figure 10.

Figure 10. Lulzbot Taz Series of Printers

B. MarkOne

An innovative 3-D printer, the Markforged MarkOne 3-D printer, as shown in Figure 11, is capable of printing continuous carbon fiber filament infused with nylon. Up to five times stronger than similar parts using regular ABS plastic, the Composite Filament Fabrication (CFF) are also up to 20 times stiffer [10]. The stiffness offered by carbon fiber strengthened the mechanical prototypes developed, including structural test components. As the most cost-effective material available by MarkForged, the fiberglass is just as strong as the carbon fiber but twice as heavy and less than half as stiff. For components needing to be durable and resistant to impact, Kevlar is the material of choice for abrasion resistance and flexibility.

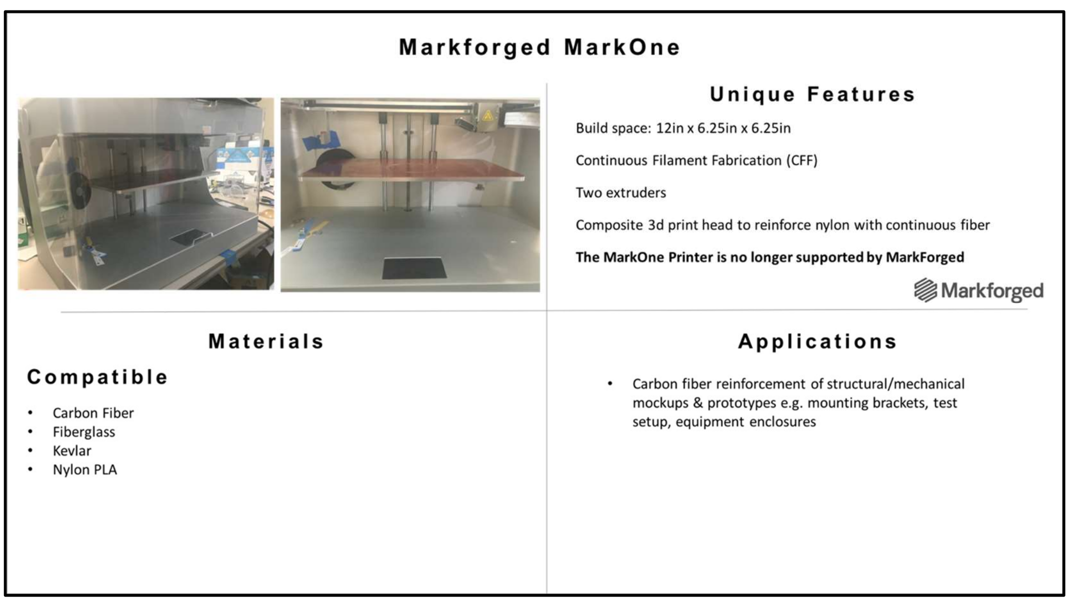

Figure 11. Markforged MarkOne Printer

No longer supported by Markforged, the MarkOne printer was upgraded to the Mark Two in 2016. It has a faster fiber printing process, the ability to strengthen minor features within all components, and increased reliability in materials, hardware and software.

C. Voxel8

The Voxel8 multi-material printer, as shown in Figure 12, is used to print electronic circuits into 3-D objects that are used in RF devices, printed antennas, and electronics. The program is demonstrating embedded efforts that include a demonstration of embedded circuitry via conductive silver ink.

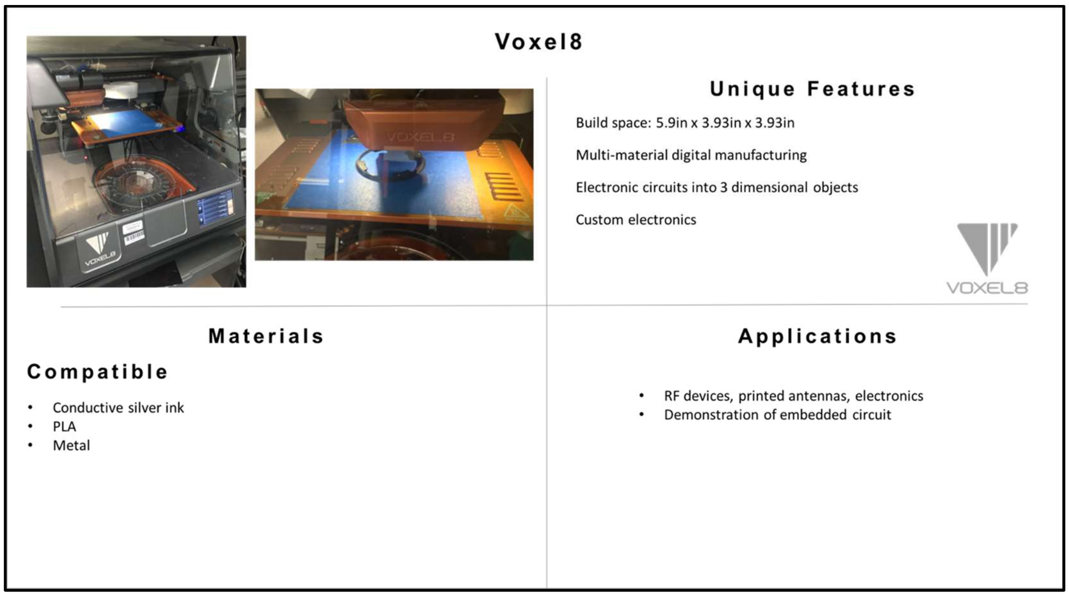

Figure 12. Voxel8 Multi-Material Printer

D. Dimatix

The high-resolution and high material conductivities provided by inkjet processes and nanoparticle materials are attractive for RF components. However, inkjet processes are not well-suited to the fabrication of the thick dielectric materials that are required. The Fujifilm Dimatix inkjet printer is capable of printing electronic circuits on a variety of flexible materials and substrates using additive manufacturing technology to build precise conductive systems. This printer, as shown in Figure 13, has supported the development of Frequency Steerable Acoustic Transducer (FSAT) impact sensors and creating customized and flexible masks, as depicted in Figure 14.

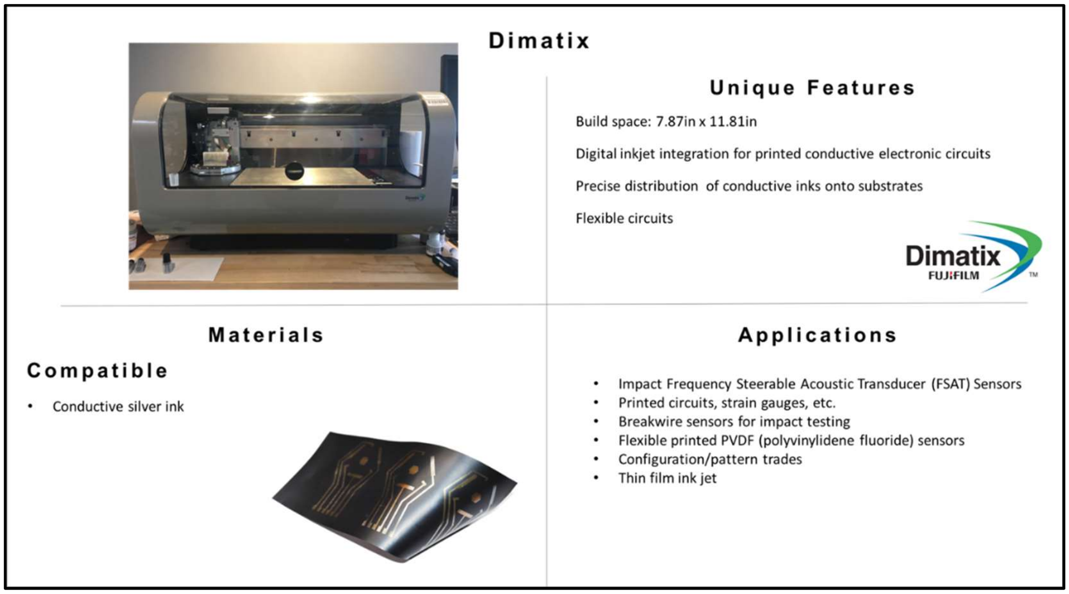

Figure 13. Dimatix Inkjet Printer

Figure 14. Dimatix Inkjet

E. MicroDispense Printhead

The MicroDispense printhead, as shown in Figure 15, allows a way to manufacture multi-material digital antenna arrays that present a number of challenges to current additive manufacturing approaches. In addition, it is desirable for printing approaches to minimize cost and maximize speed while achieving desired RF performance. An assembly of an inexpensive tool has been proposed that utilizes a significant amount of open-source software and hardware and combines features from tools, such as nScrypt, Voxel8, and Ultimaker, while optimizing for rapid and inexpensive fabrication of antenna arrays and similar embedded electronic structures.

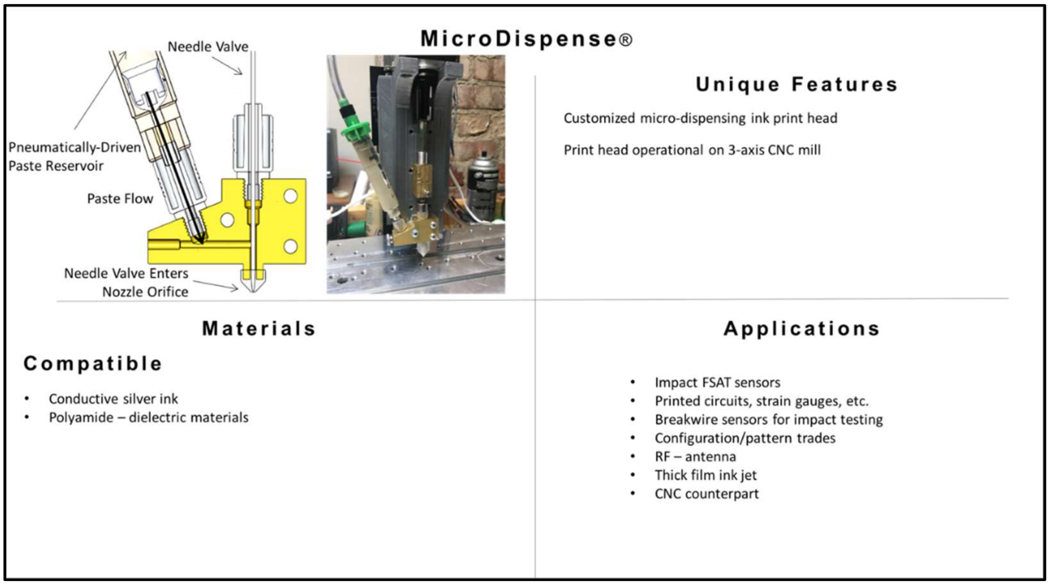

Figure 15. PRIME2's MicroDispense® Capability (EngeniusMicro)

Open-source motion control platforms, such as the Taz, the Ultimaker, the RepRap, and so forth, provide sufficient resolution that is on the order of 12 µm for Ku-band antenna prints. The limiting factor for printed component accuracy is the printhead. Open-source FDM printheads with readily available nozzles to 0.2 mm (and a few to 0.1 mm) with 0.02 mm layer heights provide sufficient resolution to realize the dielectrics required of an antenna array. The conductor print within an antenna has stricter requirements on resolution and accuracy, but the challenge is the resolution of the printhead.

The Voxel8, Fab@Home, and similar printers utilize pneumatically driven deposition of small quantities of conductive paste. Air pressure applied to a paste reservoir pushes material through the deposition nozzle. The flow is adjusted and turned on and off through control of the air pressure. This approach works for material extrusions on the order of 250 µm; however, smaller extrusions require higher operating pressures that must be relieved to stop extrusion. These higher pressures lead to excessive oozing, which limits print resolution.

Microdispense printheads solve this problem through valving the flow and are used in the electronics industry for a number of applications. Some of these operate using pulsed air, while others operate using an Archimedes screw. However, many of these approaches trade dot size for throughput and material viscosity. To minimize oozing without requiring sophisticated control of the air pressure, a needle valve approach has been employed. While other designs bring the valve close to the nozzle, the needle valve approach is designed to close off the flow directly at the nozzle orifice. The needle valve is actuated by a linear actuator or motor and can be opened and closed quickly with highly accurate starts and stops. This microdispense approach is relatively inexpensive, requiring one small machined manifold, a standard airbrush needle, a linear stepper motor, some commercially available fittings, and a 3-D printed mounting structure.

The prototype assembled was used to print traces of the same conductive ink utilized in the Voxel8 Developer's Kit. This ink has one of the highest conductivities available for a room temperature, cured, single-part conductive paste. A nozzle was printed with threads using a FormLabs Form2 SLA system. After printing, a micro-drill created the nozzle orifice. The flexibility of the system allows for smaller diameter holes to be utilized in the nozzle as well.

F. FormLabs

The Form 1 and Form 2 SLA printers, as shown in Figures 16 and 17, respectively, have been employed under the PRIME2 contract with the Form 2 incorporating upgrades as a second generation printer. The sealed optical deck, larger build volume, and improved resin cartridge contribute to these upgrades, although the overall print often consumes more time mainly due to the automated preheat cycle. The Form 1 printer was used to produce the nozzle of the MicroDispense with the Form 2 printer used for its needle valve bodies.

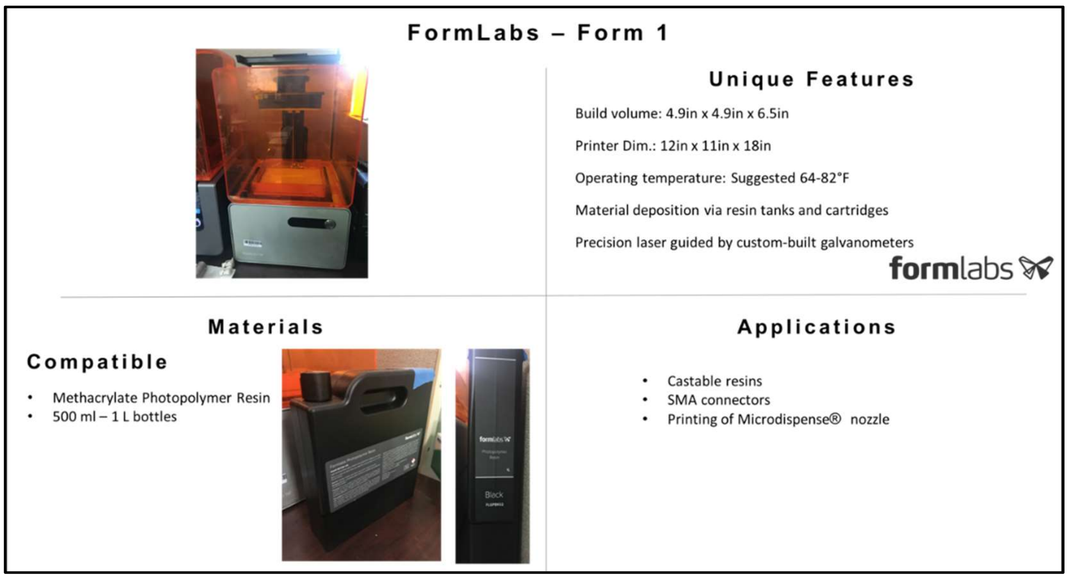

Figure 16. FormLabs Form 1 Printer

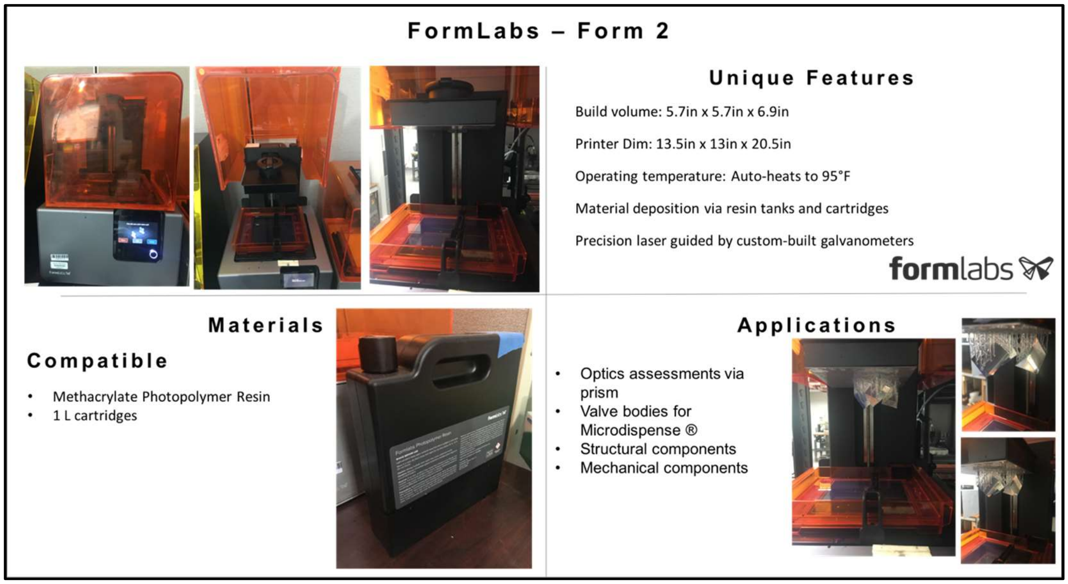

Figure 17. FormLabs Form 2 Printer

FormLabs support for the Form 1 printer will cease when current resources are no longer available, since the Form 2 printer serves the same market space with enhanced features.

G. Pegasus

The Pegasus Touch printer from Full Spectrum Laser, as shown in Figure 18, uses a UV laser beam to move with closed-loop galvo scanners to cure liquid resin for smooth printed objects. This printer is sometimes employed instead of the FormLabs printers due to its larger build area but comparable footprint. The castable resin is another differentiator for the Pegasus printer, enabling market-ready products with minimal post-processing.

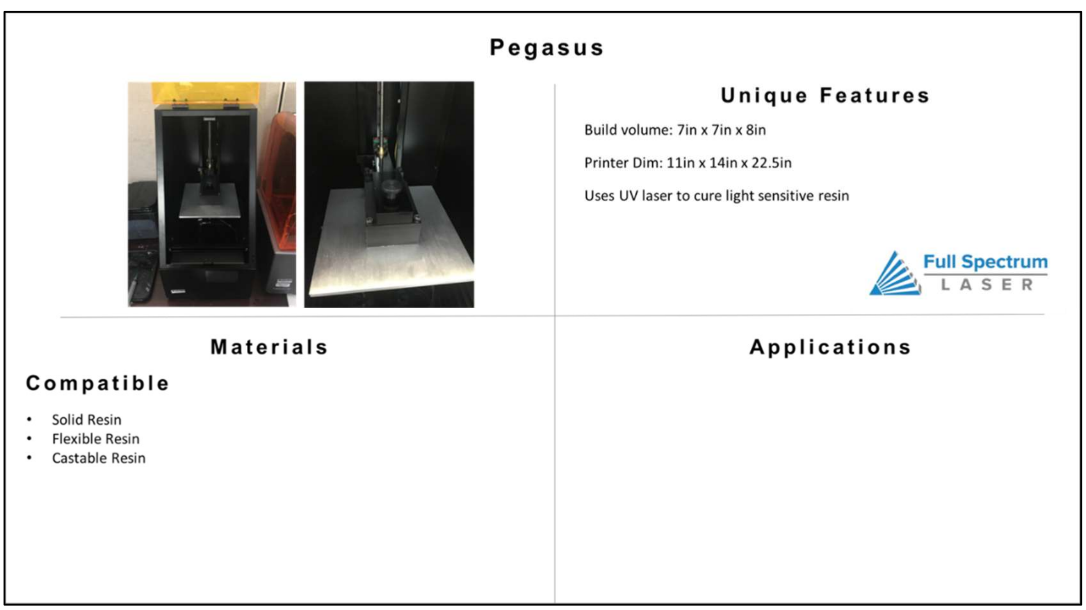

Figure 18. Pegasus Printer

VI. CONCLUSION

This report details several material properties and the printing capability at AMRDEC associated with the PRIME2 S&T program. The material test and evaluation is an ongoing effort as new materials are added. The database included in the appendix is a living document that will be continually updated. AMRDEC will be using an nScrypt printer, which will greatly enhance printing capabilities.

REFERENCES

1. Booth, J. C. et al., "Dimensional Stability—Effects of Infill Analysis for the Lulzbot (Taz) Mini Additive Manufacturing Tool (AMT)," TR-RDMR-WD-16-17, United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), Redstone Arsenal, AL, March 2016.

2. Orndorff, W., "3D Printing saves maintainers money at Hill," Ogden Air Logistics Complex, Hill Air Force Base News, 12 December 2014.

3. P. Deffenbaugh, P. et al., "Fully 3D Printed 2.4 GHz Bluetooth/Wifi Antenna," International Symposium on Microelectronics, Number 1, pp. 000914-000920, 2013.

4. Elsallal, M. et al., "3D Printed Characterization for Complex Phased Arrays and MetaMaterials," Microwave Journal, Volume 59, Number 10, October 2016.

5. Ripple, B., "AF researching advanced manufacturing techniques for replacement parts," 88th Air Base Wing Public Affairs, Hill Air Force Base News, 01 August 2016.

6. "Force Multiplying Technologies for Logistics Support to Military Operations," National Research Council, Board on Army Science and Technology, National Academies Press, 15 December 2014.

7. "Army Operations," National Research Council, Division on Engineering and Physical Sciences, Board on Army Science and Technology, National Academies Press, p. 160, 15 December 2014.

8. "3-D Printing: Sustainability Opportunities and Challenges." Business for Social Responsibility (BSR), 10 October 2017.

9. Richter K. and Wather. J., "Supply Chain Integration Challenges in Commercial Aerospace," Springer International Publishing AG, 2017.

10. Arrighi, P. A., "MarkForged Mark Two: a game changer in professional 3D printers," Aniwa, 2017, http://www.aniwaa.com/blog/markforged-mark-two-a-game-changer-in-professional-3d-printers/

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

°	degree
%	percent
@	at
&	and
°C	degrees Celsius
°F	degrees Fahrenheit
3-D, 3D, 3d	Three-Dimensional
µm	micron
ABS	acrylonitrile butadiene styrene
AMRDEC	Army Aviation and Missile Research, Development, and Engineering Center
CFF	Composite Filament Fabrication
CNC	Computer Numerical Control
DC	Direct Current
e.g	For Example
FDM	Fused Deposition Modeling
FFD	Fused Filament Deposition
FSAT	Frequency Steerable Acoustic Transducer
FY	Fiscal Year
HIPS	High Impact Polystyrene
HPLC	High-Performance Liquid Chromatography
in	inch
ISS	International Space Station
MHz	megahertz
ml	milliliter
mm	millimeter
NASA	National Aeronautics and Space Administration
PC-ABS	polycarbonate- acrylonitrile butadiene styrene
PCTPE	polyethylene terephthalate glycol-modified pasticized copolyamide Thermoplastic Elastomer
PEEK	polyether ether ketone
PEI	polyetherimide
PETG	polyethylene terephthalate glycol

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONCLUDED)

PETT	polyethylene terephthalate
PLA	Polylactic Acid
PMMA	polymethyl methacrylate
PRIME2	PRIntable Materials With Embedded Electronics
PVA	polyvinyl alcohol
PVDF	polyvinylidene fluoride
Rel.	Relative
RF	Radio Frequency
S&T	Science and Technology
S/m	siemens per meter
sec	second
SLA	Stereolithography
SMA	Sub-Miniature A
Temp	Temperature
TPE	Thermoplastic Elastomer
U.S.	United States
UV	Ultraviolet
WDI	Weapons Development and Integration
x	-by-

APPENDIX

MATERIAL DATABASE COLUMNS DEFINED

Material Database Columns Defined:

Column#	Column Label	Definition
B	Sample	Line Item
C	Material	Printing material (such as filament type)
D	Material Vendor	Provider
E	Printer	3D Printer type/Vendor
F	Nominal Filament Diameter (mm)	For filaments, the actual commercial diameter – dictates printhead type
G	Published Glass Transition Temp (°C)	The reversible transition from a hard state into a viscous or rubbery state
H	Sample Diameter (m)	Test article diameter
I	Sample Thickness (m)	Test article thickness
J	Sample Area (m^2)	Test article cross sectional area
K	% Infill	Infill setting for the printer
L	1st Layer Height (mm)	First printed layer thickness/height (z-direction)
M	Top/bottom shell height (mm)	This is the height of solid layers on the top and bottom. Top/Bot shells are usually 2 or 3 layers thick.
N	Layer height (mm)	Printer defined layer height for FDM
O	Cv(F)	I think this is calculated capacitance of the gap between the test probes in a vacuum
P	C(F) @ 10kHz	Measure Capacitance at 10 kHz
Q	ε_r = C / Cv	Relative Permittivity
R	R(ohm) @ 100Hz	Measured Resistance of material sample
S	Rho (ohm-m)	Resistivity of material sample
T	S/m	Siemens/m
U	Solvents	Suggested solvent for material
V	Notes	

Sample#	Material	Material Vendor	Printer	Nominal Filament Diameter (mm)	Published Glass Transistion Temp. (C°)	Sample Diameter (m)
1	PLA	Voxel8	Voxel8	1.75	65	0.025
2	PLA	Voxel8	Voxel8	1.75	65	0.025
3	ABS	Lulzbot	Taz6	3	105	0.025
4	ABS	Lulzbot	Taz6	3	105	0.025
5	PLA	Voxel8	Voxel8	1.75	65	0.025
6	ABS	Lulzbot	Taz6	3	105	0.025
7	ABS	Lulzbot	Taz6	3	105	0.025
8	ABS	Lulzbot	Taz6	3	105	0.025
9	ABS	Lulzbot	Taz6	3	105	0.025
10	Conductive PLA	Protopasta	Taz6	3	65	0.025
11	SS PLA	Protopasta	Taz6	3	65	0.025
12	Copper PLA	colorFabb	Taz6	3	65	0.025
13	HIPS	Lulzbot	Taz6	3	100	0.025
14	HIPS	Lulzbot	Taz6	3	100	0.025
15	HIPS	Lulzbot	Taz6	3	100	0.025
16	HIPS	Lulzbot	Taz6	3	100	0.025
17	ABS	Lulzbot	Taz6	3	105	0.025
18	ABS	Lulzbot	Taz6	3	105	0.025
19	ABS	Lulzbot	Taz6	3	105	0.025
20	PLA	Voxel8	Voxel8	1.75	65	0.025
21	PLA	Voxel8	Voxel8	1.75	65	0.025
22	618 Nylon	Taulman	Taz6	3	68	0.025
23a	HTPLA, pre heat treat	Protopasta	Taz6	3	120	0.025
23b	HTPLA, post heat treat	Protopasta	Taz6	3	120	0.025
24	nGen	colorFabb	Taz6	3	85	0.025
25	Bronze PLA	colorFabb	Taz6	3	65	0.025
26	Magnetic PLA	Protopasta	Taz6	3	65	0.025
27	HIPS Sheet Stock	McMaster Carr	Sheet Stock	-	100	0.025
28	HIPS	Lulzbot	Taz6	3	100	0.025
29	ABS Sheet Stock	McMaster Carr	Sheet Stock	-	105	0.025
30	PEEK Sheet Stock	McMaster Carr	Sheet Stock	-	143	0.025
31	PEEK		Taz6 modified	3	143	0.025

32	High Temp Resin	Formlabs	Form2	3	289	0.025
33	Black Resin	Formlabs	Form2	3	73	0.025
34	Tough Resin	Formlabs	Form2	3	48.5	0.025
35	ESD PC	3DXTECH	Taz6	3	147	0.025
36	PC/ASA	3DXTECH	Taz6	3	126	0.025
37	PC/ABS	3DXTECH	Taz6	3	137	0.025
38	ASA	3DXTECH	Taz6	3	104	0.025
39	Ceramic Resin	Tethon3d	Form1+	3	-	0.025
40	ESD PC	3DXTECH	Taz6	3	147	0.025
41	PC/ABS	3DXTECH	Taz6	3	137	0.025
42	PC/ASA	3DXTECH	Taz6	3	126	0.025
43	ASA	3DXTECH	Taz6	3	104	0.025
44	Conductive PLA	Protopasta	Taz6	3	65	0.025
45	SS PLA	Protopasta	Taz6	3	65	0.025
46	Copper PLA	colorFabb	Taz6	3	65	0.025
47	Flexible V2	Formlabs	Form 2	3		0.025
48	PETG	MatterHackers	Taz6	1.75		0.025
49	PETG	MatterHackers	Taz6	1.75		0.025
50	PETG	MatterHackers	Taz6	1.75		0.025
51	PETG	MatterHackers	Taz6	1.75		0.025
52	PC-ABS	3DXTECH	Taz6	3		0.025
53	PC-ABS	3DXTECH	Taz6	3		0.025
54	PC-ABS	3DXTECH	Taz6	3		0.025
55	nGen	colorFabb	Taz Mini	3		0.025
56	nGen	colorFabb	Taz Mini	3		0.025
57	nGen	colorFabb	Taz Mini	3		0.025

Sample#	Material	Sample Thickness (m)	Sample Area (m^2)	% Infill	1st layer height (mm)	Top/bot shell height (mm)
1	PLA	0.002	#VALUE!	20	0.3	0.3
2	PLA	0.002	#VALUE!	20	0.3	0.3
3	ABS	0.002	#VALUE!	100	0.425	1.1
4	ABS	0.002	#VALUE!	100	0.425	1.1
5	PLA	0.002	#VALUE!	100	0.3	0.3
6	ABS	0.002	#VALUE!	20	0.425	0.760
7	ABS	0.002	#VALUE!	20	0.425	1.100
8	ABS	0.002	#VALUE!	20	0.425	1.080
9	ABS	0.002	#VALUE!	20	0.220	0.22
10	Conductive PLA	0.002	#VALUE!	80	0.425	1.000
11	SS PLA	0.002	#VALUE!	20	0.425	1.000
12	Copper PLA	0.002	#VALUE!	20	0.425	1.000
13	HIPS	0.002	#VALUE!	20	0.425	1.000
14	HIPS	0.002	#VALUE!	20	0.425	0.760
15	HIPS	0.002	#VALUE!	20	0.425	1.080
16	HIPS	0.002	#VALUE!	20	0.25	0.25
17	ABS	0.001	#VALUE!	100	0.425	1.100
18	ABS	0.0015	#VALUE!	100	0.425	1.100
19	ABS	0.003	#VALUE!	100	0.425	1.100
20	PLA	0.001	#VALUE!	100	0.425	1.000
21	PLA	0.0015	#VALUE!	100	0.425	1.000
22	618 Nylon	0.002	#VALUE!	100	0.425	1.2
23a	HTPLA, pre heat treat	0.002	#VALUE!	100	0.425	0.8
23b	HTPLA, post heat treat	0.002	#VALUE!	100	0.425	0.8
24	nGen	0.002	#VALUE!	100	0.425	1
25	Bronze PLA	0.002	#VALUE!	100	0.425	1
26	Magnetic PLA	0.002	#VALUE!	100	0.425	1
27	HIPS Sheet Stock	0.0033	#VALUE!	-	-	-
28	HIPS	0.002	#VALUE!	100	0.425	1.000
29	ABS Sheet Stock	0.0033	#VALUE!	-	-	-
30	PEEK Sheet Stock	0.00345	#VALUE!	-	-	-
31	PEEK	0.002	#VALUE!	100	0.425	1.000
32	High Temp Resin	0.002	#VALUE!	100	-	-
33	Black Resin	0.002	#VALUE!	100	-	-

34	Tough Resin	0.002	#VALUE!	100	-	-
35	ESD PC	0.002	#VALUE!	80	0.425	1.14
36	PC/ASA	0.002	#VALUE!	80	0.425	1.14
37	PC/ABS	0.002	#VALUE!	80	0.425	1.14
38	ASA	0.002	#VALUE!	80	0.425	1.14
39	Ceramic Resin	0.002	#VALUE!	100	-	-
40	ESD PC	0.002	#VALUE!	100	0.425	1.14
41	PC/ABS	0.0023	#VALUE!	100	0.425	1.14
42	PC/ASA	0.002	#VALUE!	100	0.425	1.14
43	ASA	0.002	#VALUE!	100	0.425	1.14
44	Conductive PLA	0.002	#VALUE!	100	0.425	1.000
45	SS PLA	0.002	#VALUE!	100	0.425	1.000
46	Copper PLA	0.002	#VALUE!	100	0.425	1.000
47	Flexible V2	0.002	#VALUE!	100	0.425	1.000
48	PETG	0.0021	#VALUE!	100	0.250	1.000
49	PETG	0.0021	#VALUE!	60	0.250	1.000
50	PETG	0.0021	#VALUE!	40	0.250	1.000
51	PETG	0.0021	#VALUE!	20	0.250	1.000
52	PC-ABS	0.0017	#VALUE!	60	0.250	1.000
53	PC-ABS	0.0017	#VALUE!	40	0.250	1.000
54	PC-ABS	0.0017	#VALUE!	20	0.250	1.000
55	nGen	0.00195	#VALUE!	60	0.250	1.000
56	nGen	0.00195	#VALUE!	40	0.250	1.000
57	nGen	0.00195	#VALUE!	20	0.250	1.000

Sample#	Material	Layer height (mm)	C_v (F)	C (F) @ 10 kHz	ε_r	R (ohm) @ 100 Hz
1	PLA	0.19	#REF!	3.96E-12	#REF!	-
2	PLA	0.19	#REF!	5.38E-12	#REF!	-
3	ABS	0.22	#REF!	7.71E-12	#REF!	-
4	ABS	0.22	#REF!	7.72E-12	#REF!	-
5	PLA	0.19	#REF!	7.41E-12	#REF!	-
6	ABS	0.380	#REF!	5.88E-12	#REF!	-
7	ABS	0.220	#REF!	5.66E-12	#REF!	-
8	ABS	0.180	#REF!	6.51E-12	#REF!	-
9	ABS	0.22	#REF!	5.36E-12	#REF!	-
10	Conductive PLA	0.250	#REF!	-	-	10.2
11	SS PLA	0.250	#REF!	1.47E-11	#REF!	2.39E+07
12	Copper PLA	0.250	#REF!	1.83E-11	#REF!	-
13	HIPS	0.250	#REF!	6.43E-12	#REF!	-
14	HIPS	0.380	#REF!	4.94E-12	#REF!	-
15	HIPS	0.180	#REF!	5.61E-12	#REF!	-
16	HIPS	0.25	#REF!	3.45E-12	#REF!	-
17	ABS	0.220	#REF!	8.45E-12	#REF!	-
18	ABS	0.220	#REF!	6.28E-12	#REF!	-
19	ABS	0.220	#REF!	4.00E-12	#REF!	-
20	PLA	0.250	#REF!	1.27E-11	#REF!	-
21	PLA	0.250	#REF!	9.50E-12	#REF!	-
22	618 Nylon	0.3	#REF!	6.55E-12	#REF!	-
23a	HTPLA, pre heat treat	0.2	#REF!	7.03E-12	#REF!	-
23b	HTPLA, post heat treat	0.2	#REF!	7.00E-12	#REF!	-
24	nGen	0.25	#REF!	1.35E-11	#REF!	-
25	Bronze PLA	0.25	#REF!	1.75E-11	#REF!	-
26	Magnetic PLA	0.25	#REF!	1.08E-11	#REF!	-
27	HIPS Sheet Stock	-	#REF!	5.00E-12	#REF!	-
28	HIPS	0.250	#REF!	6.48E-12	#REF!	-
29	ABS Sheet Stock	-	#REF!	5.56E-12	#REF!	-
30	PEEK Sheet Stock	-	#REF!	5.40E-12	#REF!	-
31	PEEK	0.250	#REF!	6.90E-12	#REF!	-
32	High Temp Resin	0.05	#REF!	8.00E-12	#REF!	-
33	Black Resin	0.05	#REF!	1.11E-11	#REF!	-
34	Tough Resin	0.05	#REF!	1.10E-11	#REF!	-

35	ESD PC	0.38	#REF!	2.07E-11	#REF!	-
36	PC/ASA	0.38	#REF!	7.90E-12	#REF!	-
37	PC/ABS	0.38	#REF!	6.30E-12	#REF!	-
38	ASA	0.38	#REF!	7.75E-12	#REF!	-
39	Ceramic Resin	0.05	#REF!	1.15E-11	#REF!	-
40	ESD PC	0.38	#REF!	1.59E-11	#REF!	-
41	PC/ABS	0.38	#REF!	1.09E-11	#REF!	-
42	PC/ASA	0.38	#REF!	7.42E-12	#REF!	-
43	ASA	0.38	#REF!	7.90E-12	#REF!	-
44	Conductive PLA	0.250	#REF!	-	-	70
45	SS PLA	0.250	#REF!	1.63E-11	#REF!	-
46	Copper PLA	0.250	#REF!	1.50E-11	#REF!	-
47	Flexible V2	0.250	#REF!	2.50E-11	#REF!	-
48	PETG	0.250	#REF!	1.27E-11	#REF!	-
49	PETG	0.250	#REF!	1.12E-11	#REF!	-
50	PETG	0.250	#REF!	9.67E-12	#REF!	-
51	PETG	0.250	#REF!	9.40E-12	#REF!	-
52	PC-ABS	0.250	#REF!	1.43E-11	#REF!	-
53	PC-ABS	0.250	#REF!	1.27E-11	#REF!	-
54	PC-ABS	0.250	#REF!	1.04E-11	#REF!	-
55	nGen	0.250	#REF!	1.33E-11	#REF!	-
56	nGen	0.250	#REF!	1.28E-11	#REF!	-
57	nGen	0.250	#REF!	1.24E-11	#REF!	-

Sample#	Material	rho (ohm-m)	S/m	Solvents	Notes
1	PLA	-	-	-Tetrahydrofuran -Weldon	
2	PLA	-	-	-Tetrahydrofuran -Weldon	
3	ABS	-	-	Acetone	
4	ABS	-	-	Acetone	
5	PLA	-	-	-Tetrahydrofuran -Weldon	
6	ABS	-	-	Acetone	
7	ABS	-	-	Acetone	
8	ABS	-	-	Acetone	
9	ABS	-	-	Acetone	
10	Conductive PLA	#VALUE!	#VALUE!	-Tetrahydrofuran -Weldon	
11	SS PLA	#VALUE!	#VALUE!	-Tetrahydrofuran -Weldon	
12	Copper PLA	-	-	-Tetrahydrofuran -Weldon	
13	HIPS	-	-	Limonene	
14	HIPS	-	-	Limonene	
15	HIPS	-	-	Limonene	
16	HIPS	-	-	Limonene	Bad print quality
17	ABS	-	-	Acetone	*Note different thickness
18	ABS	-	-	Acetone	*Note different thickness
19	ABS	-	-	Acetone	*Note different thickness
20	PLA	-	-	Acetone	*Note different thickness
21	PLA	-	-	Acetone	*Note different thickness
22	618 Nylon	-	-	-Acetic Acid* -Phenols* -HCl* *Not Tested	
23a	HTPLA, pre heat treat	-	-	-Tetrahydrofuran -Weldon	
23b	HTPLA, post heat treat	-	-	-Tetrahydrofuran -Weldon	heat treated at 230F for 1 hour
24	nGen	-	-		

25	Bronze PLA	-	-	-Tetrahydrofuran -Weldon	
26	Magnetic PLA	-	-	-Tetrahydrofuran -Weldon	
27	HIPS Sheet	-	-	Limonene	*Note different thickness
28	HIPS	-	-	Limonene	
29	ABS Sheet Stock	-	-	Acetone	*Note different thickness
30	PEEK Sheet Stock	-	-	-Fuming sulphuric acid* *Not Tested	*Note different thickness
31	PEEK	-	-	-Fuming sulphuric acid* *Not Tested	Top surface very rough
32	High Temp	-	-	-	
33	Black Resin	-	-	-	
34	Tough Resin	-	-	-	
35	ESD PC	-	-	Weldon	
36	PC/ASA	-	-	-Weldon -Acetone	
37	PC/ABS	-	-	-Weldon -Acetone	
38	ASA	-	-	-Weldon -Acetone	
39	Ceramic Resin	-	-	-	
40	ESD PC	-	-	Weldon	
41	PC/ABS	-	-	Weldon	
42	PC/ASA	-	-	Weldon	
43	ASA	-	-		
44	Conductive PLA	#VALUE!	#VALUE!	-Tetrahydrofuran -Weldon	
45	SS PLA	-	-	-Tetrahydrofuran -Weldon	
46	Copper PLA	-	-	-Tetrahydrofuran -Weldon	
47	Flexible V2	-	-	-Tetrahydrofuran -Weldon	
48	PETG	-	-	-Tetrahydrofuran -Weldon	
49	PETG	-	-	-Tetrahydrofuran -Weldon	

50	PETG	-	-	-Tetrahydrofuran -Weldon	
51	PETG	-	-	-Tetrahydrofuran -Weldon	
52	PC-ABS	-	-	-Tetrahydrofuran -Weldon	
53	PC-ABS	-	-	-Tetrahydrofuran -Weldon	
54	PC-ABS	-	-	-Tetrahydrofuran -Weldon	
55	nGen	-	-	-Tetrahydrofuran -Weldon	
56	nGen	-	-	-Tetrahydrofuran -Weldon	
57	nGen	-	-	-Tetrahydrofuran -Weldon	